E47-62
MARCH 19, 1962

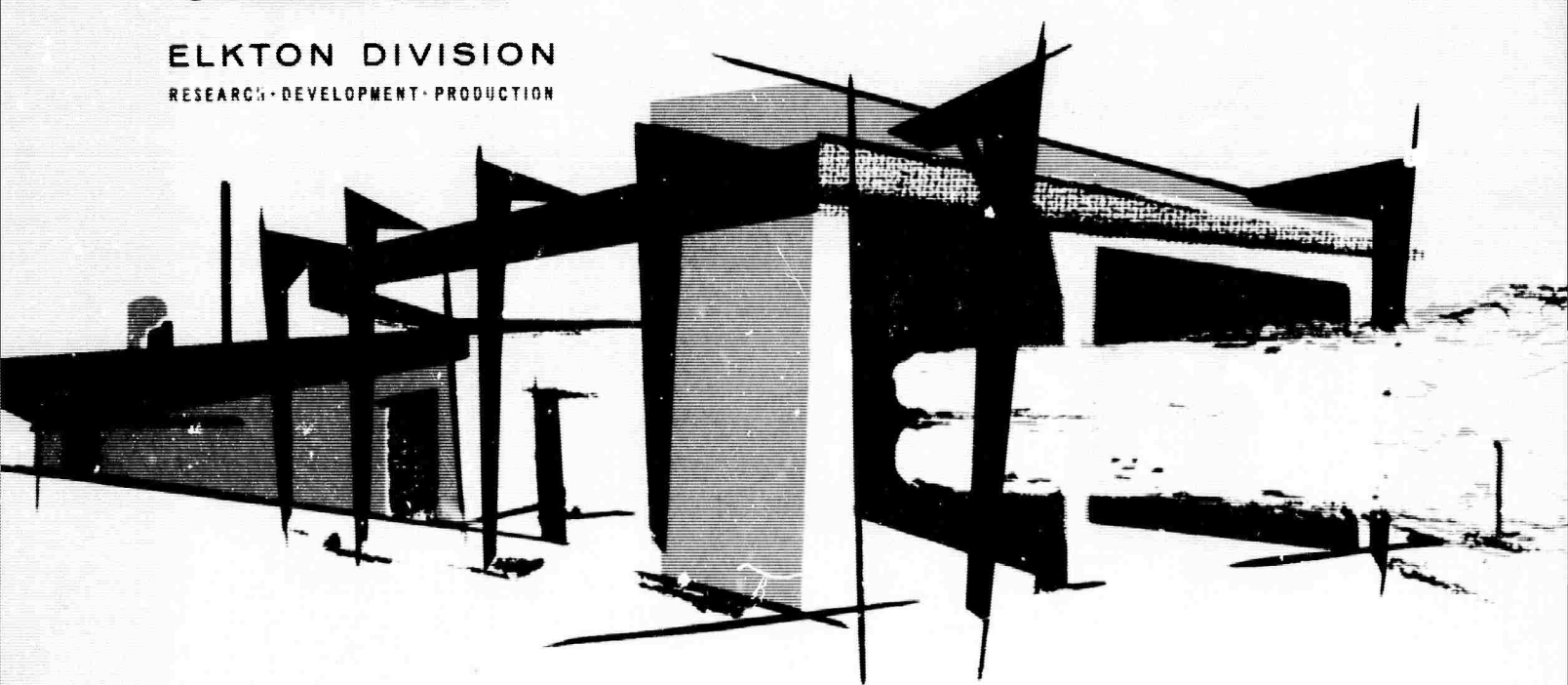## *Thiokol*

ELKTON DIVISION
RESEARCH · DEVELOPMENT · PRODUCTION

EXPERIMENTS FOR THE MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF
A BURNING SOLID PROPELLANT, QUARTERLY TECHNICAL REPORT NO. 3,
CONTRACT NO. Nonr 3473(00)

2601

E47-62

THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

"EXPERIMENTS FOR THE MEASUREMENT OF THE
ACOUSTIC IMPEDANCE OF A BURNING SOLID PROPELLANT"

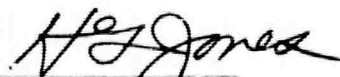QUARTERLY TECHNICAL REPORT NO. 3

NOVEMBER 15, 1961 THROUGH FEBRUARY 15, 1962

PREPARED FOR:

Office of Naval Research
Power Branch, Code 426
Department of the Navy
Washington 25, D. C.

Contract No. Nonr 3473(00)
ARPA Order No. 23-61, Task 5
Project Code No. 9100

MARCH 19, 1962

H. G. Jones
General Manager

FOREWORD

This quarterly report covering the period from November 15, 1961, to February 15, 1962, has been prepared by the Elkton Division of Thiokol Chemical Corporation and describes the continuing effort on Contract Nonr 3473(00), a program to develop instrumentation and to measure the acoustic impedance of a burning solid propellant.

The studies have been conducted at the Thiokol research laboratories at Elkton, Maryland. Contributors to the program technical effort during this reporting period were: Edward S. Stern, Principal Investigator, Research Section; James R. Woodyard, Physicist, Research Section; and Dr. Alvin O. Converse, Program Consultant, Carnegie Institute of Technology.

The studies have been conducted under the general supervision of Dr. C. C. Alfieri, Head, Research Section, and Dr. G. R. Leader, Head, Physical and Analytical Chemistry Group.

The program manager is Mr. M. David Rosenberg.

TABLE OF CONTENTS

ABSTRACT

This report describes the progress made during the third quarter of this research program to measure the acoustic impedance of a burning solid propellant.

The acoustic impedance of acoustical materials can be determined with the present instrumentation. Data obtained using the Elkton test chamber are compared with typical data obtained from the literature. Variations due to mounting and thickness of test specimens are discussed.

Details of the microphone and sound driver performance are presented. Linearity tests of the equipment have indicated possible operational problems which must be checked further.

A supplementary bibliography of applicable references is included as an appendix to this report.

I. INTRODUCTION

This program, being pursued under Contract Nonr 3473(00), ARPA Order No. 23-61, consists of research studies to develop instrumentation and to measure the acoustic impedance of a burning solid propellant. Its objective is to evaluate a modification of the method developed by O. K. Mawardi (references 1 and 2) to measure the impedance of inert materials (passive tests). This technique will be considered feasible for this program if it can be shown that burning propellant acts as an amplifier of acoustic energy (active tests).

Briefly, the current study consists of four parts:

1) Construction and testing a conventional apparatus utilizing the technique developed by Mawardi;

2) Adapting the conventional apparatus for use with burning propellant;

3) Checking the modified apparatus with known materials (i.e., materials studied in the first phase); and

4) Measuring the impedance of a burning propellant surface.

Part 1 has been completed and the effort on Part 2 is now in the final stages of completion. Concurrently, the initial steps of Part 3 have been accomplished. Parts 3 and 4 are scheduled for completion in the fourth quarter.

A summary of existing theoretical and experimental work upon which this study is based was presented in Quarterly Report No. 1 (reference 3). Additional references that have been reviewed during the current period are presented as an appendix to this report.

II. TECHNICAL PROGRAM

Theoretical treatments (references 7, 8, and 9) of solid propellant rocket instability require knowledge of the reaction of the burning propellant surface to an acoustic disturbance. This boundary may be represented by the specific acoustic impedance, and it is important that this impedance be measured when the pressure oscillations are small so that linear theory applies.

The experimental technique being developed consists of a surface method for measuring acoustic impedance based on techniques developed by Mawardi (references 1 and 2). As described in Quarterly Reports 1 and 2, the sample chamber is chosen so that it acts as a lumped acoustical element. Sound is delivered to the chamber through a wire-filled tube and is emitted through a circular slot so that the sound source appears as a narrow circular ring in one end of the chamber. The source was designed to suppress the first symmetrical and all asymmetrical modes of vibration and is of as high an impedance as possible, so that its volume velocity remains constant with changes in loading impedance. Similarly, the probe microphone chosen has a very high acoustic impedance.

A. Test Procedure

The equipment is checked at a frequency of 1000 c/s (arbitrary) before experimentation is begun. At this frequency, the oscillator output is set at one volt. The signal is fed to the driver amplifier and the gain adjusted to maintain a five-volt output. This wave form to the driver and the output of the mocrophone are observed and monitored on an oscilloscope. A chamber body size is selected, depending upon the

frequency range being considered. With the imput voltage to the driver held constant, the output voltage and phase of the microphone are recorded as a result of the excitation throughout the frequency range under study. The corresponding outputs from the microphone for a constant input current with a rigid termination and with a sample are related, so that the sample impedance can be calculated by:

$$Z_m = Z_c \left(\frac{1}{\overline{B_e j \emptyset - 1}} \right)$$

where: Z_m = impedance of sample

Z_c = impedance of chamber without sample

E_1 = voltage from microphone without sample

E_2 = voltage from microphone with sample

$B = \dfrac{E_1}{E_2}$

$\emptyset$ = phase angle

B. Inert Materials Tested

The energy absorbing ability of an acoustical material at a given frequency is most commonly specified by an "absorption coefficient." Detailed accoustical theory shows that the specific acoustic impedance has much wider applicability in describing a given material. This quantity, a complex number, varies with frequency and may vary with the angle of incidence of the sound. Since the complex specific acoustic impedance contains two parts, it cannot generally be calculated from any single value of any of the coefficients.

Under the special condition of normal incidence, Beranek (reference 5) relates the sound absorption coefficient, α_n, to the normal specific acoustic impedance.

$$\alpha_n = 1 - \left(\frac{Z/\rho c - 1}{Z/\rho c + 1}\right)^2$$

These conditions exist in the method under investigation in this study.

The sound absorption coefficients of materials tested have been determined by ASTM test method C423-60T. Coefficients for individual frequencies at octave intervals from 125 to 4000 cycles per second are shown in Table I. These coefficients were obtained from tests conducted by the Acoustical Materials Association and were reported in their Bulletin XX1 (1961). The weight of the material is given to identify the type of sample tested.

By this method absorption coefficients can generally be determined to an incremental precision of ± 0.01 over a range from 0.04 to 1.00. It is difficult to state the corresponding precision of impedance measurements in simple terms, but it will vary between approximately 0.05 and 0.2 ρ c units.

To test the general validity of data, absorption coefficients were calculated using the chart in reference 5 for converting from the real and imaginary parts of the impedance ratio to the normal incidence absorption coefficient. A comparison of sound absorption coefficients for the Permacoustic sample is shown in the following table.

Frequency, c/s	Sound Absorption Coefficients	
	AMA Reported	Elkton Calculated
250	0.24	0.18
500	0.84	0.45
1000	0.98	0.65

TABLE I

DESCRIPTION OF INERT MATERIALS TESTED

		Sound Absorption Coefficient							
Material	Thickness, inches	125 cps	250 cps	500 cps	1,000 cps	2,000 cps	4,000 cps	Weight lb/ft^2	Surface
Airocoustic[1]	0.15	0.35	0.43	0.40	0.74	0.85	0.78	0 70	Unpainted
Permacoustic[2]	0.75	0.12	0.24	0.84	0.98	0.86	0.81	1.2	Fissured, painted
Sanacoustic Pad[3]	1.0	0.48	0.60	0.55	0.67	0.70	0.50	0.042	
Panelglass[4] (a)	1.25	0.88	0.83	0.85	0.90	0.88	0.80	0.21	Painted, fine
(b)	1.25	0.86	0.76	0.81	0.92	0.86	0.73	0.21	texture

---

[1] A sound absorbent duct lining. Mounted on 24-gauge sheet iron.

[2] A mineral wool fiber with binder in monolithic construction. Cemented to plaster board with 1/8-inch air space.

[3] A mineral fiber mechanically mounted on special metal supports. Values vary with the depth of air space behind the acoustical material.

[4] A fiberglass material mounted as in (3)

(a) Mounting with 9 3/8-inch air space

(b) Mounting with 16-inch air space

These differences are believed to be due to the method of mounting samples. For example, with two samples of Permacoustic, one mounted with 1/8-inch air space and the other mounted with a 6-inch air space, the following variation in coefficients has been reported:

Frequency, c/s	Sound Absorption Coefficients	
	1/8-Inch Air Space	6-Inch Air Space
250	0.24	0.71
500	0.84	0.75
1000	0.9	0.76

Beranek (reference 4) states that w th smal' samples the variations observeu were definitely related to mounting conditions and could not be due to variations in normal impedance with angle of incidence. The conclusion is that small changes in mounting conditions have a more pronounced effect on the results predicted from small tube sample measurements than do variations of Z with angle of incidence.

Figures 1, 2, and 3 show a comparison between data obtained using the Elkton test chamber and typical data obtained from the literature. Here, too, differences can be attributed to variations in mountings and sample thickness.

C. Microphone Performance

In almost every electronic instrumentation used to measure nonelectrical quantities, the transducer is the weakest link. Consequently, the accuracy and reliability of the measurements depend on the choice and correct use of the transducer. The condenser microphone offers high stability and flat frequency characteristics with a reasonably high sensitivity.
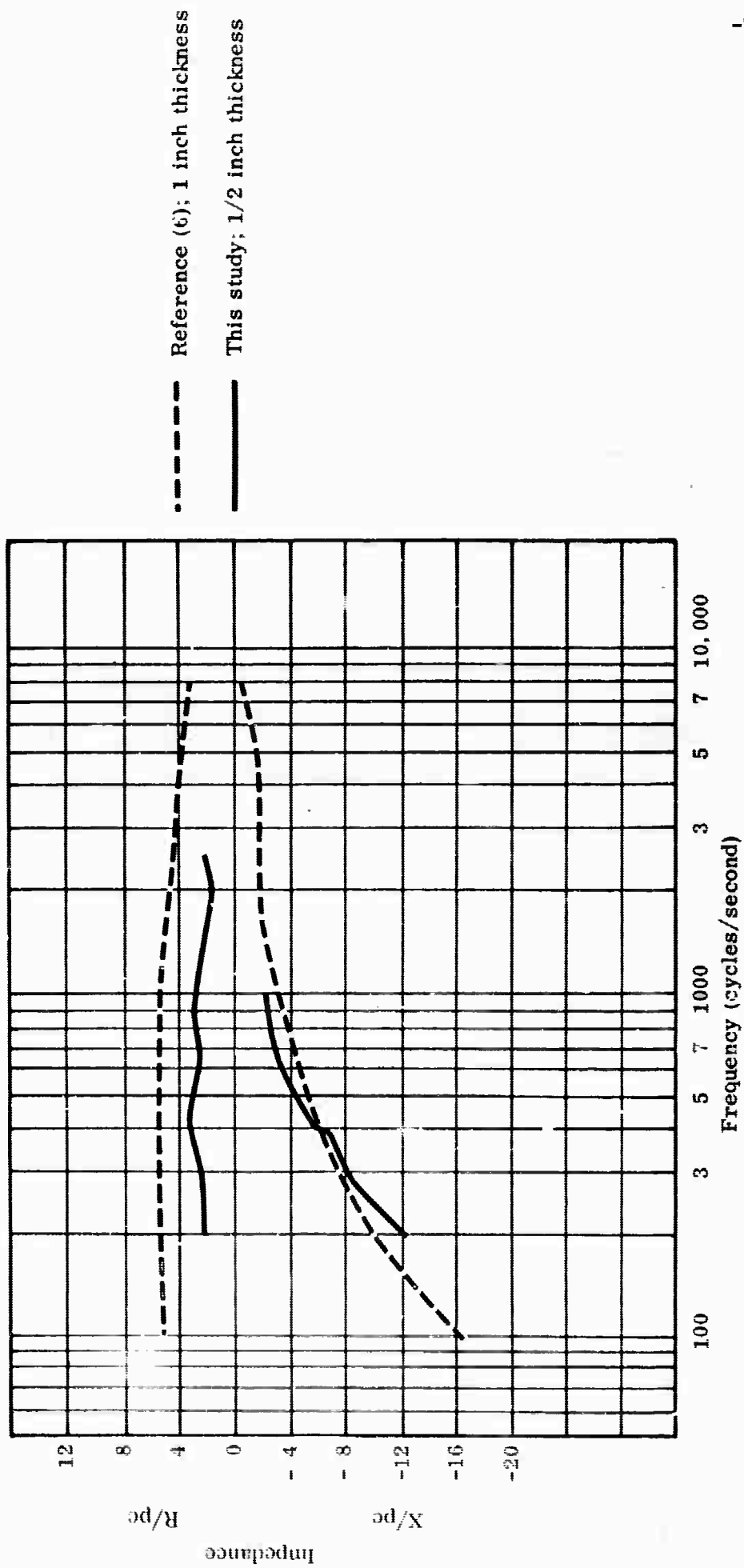
A-3821

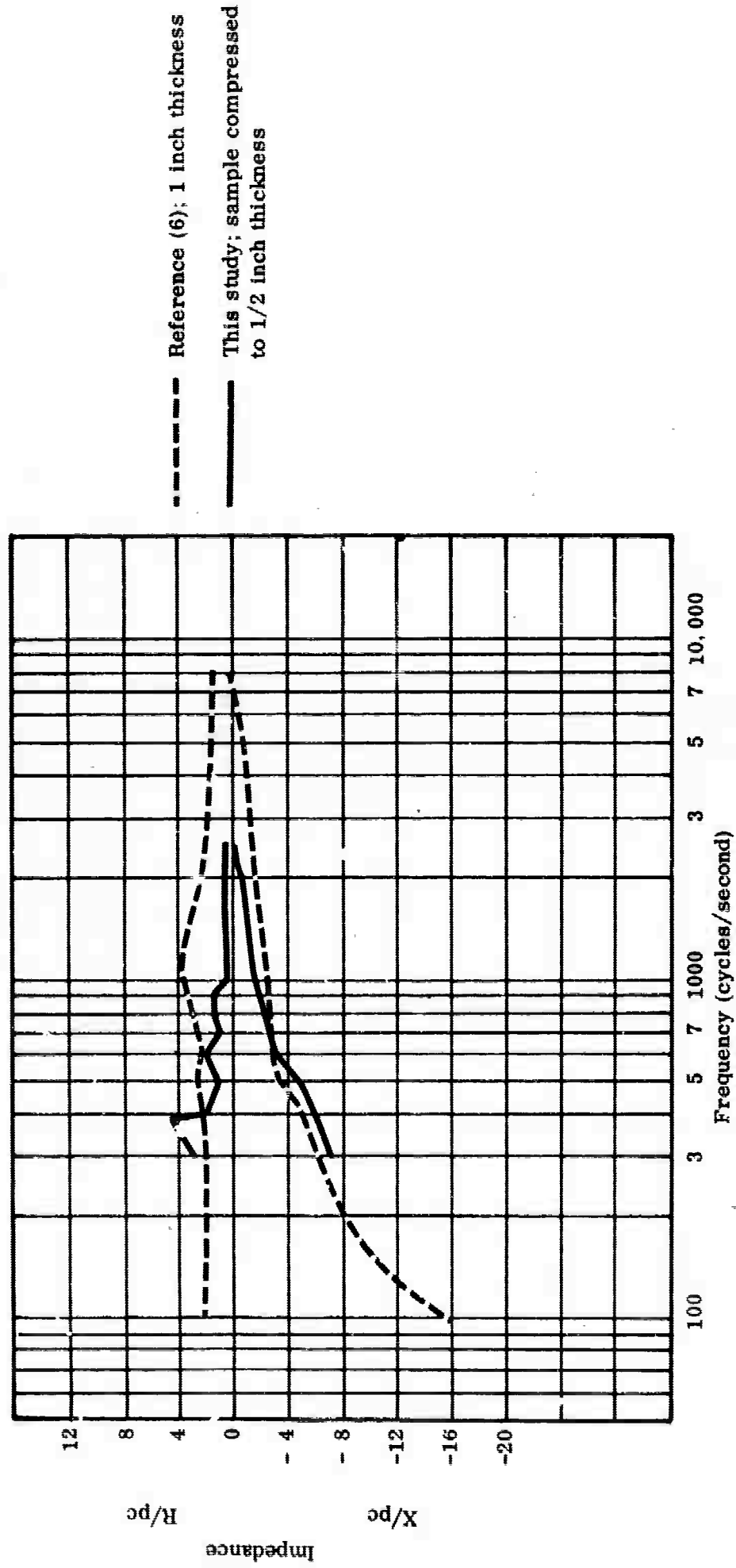FIGURE 1. FREQUENCY VERSUS IMPEDANCE FOR JOhNS–MANVILLE AIRACOUSTIC

A-3822

FIGURE 2. FREQUENCY VERSUS IMPEDANCE FOR JOHNS–MANVILLE SANₐCOUSTIC PAD.

Reference (6); 1 inch thickness

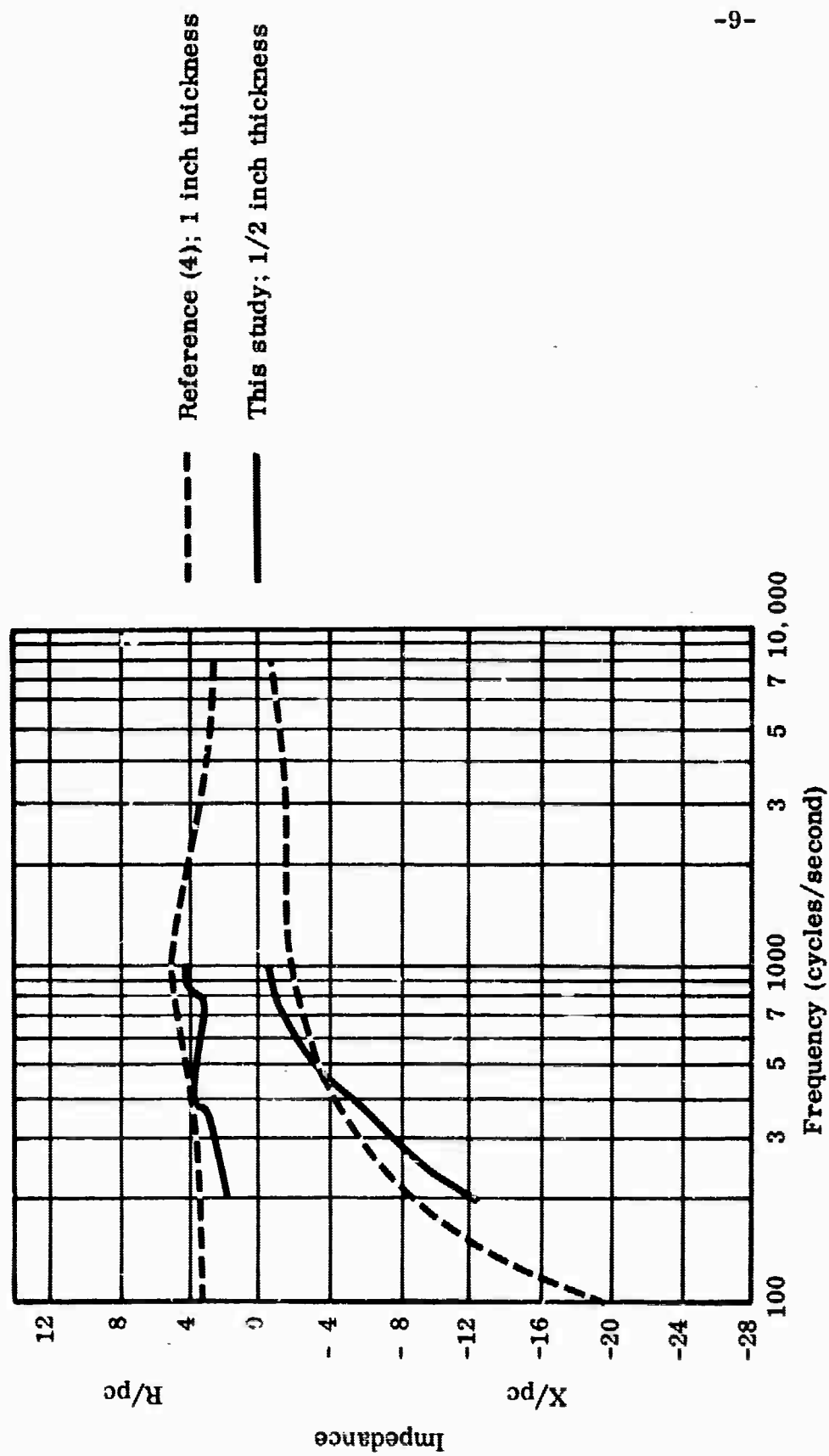This study; sample compressed to 1/2 inch thickness

A-3823

FIGURE 3. FREQUENCY VERSUS IMPEDANCE FOR JOHNS-MANVILLE PERMACOUSTIC

The condenser microphone consists basically of a thin metal diaphragm and a back plate constituting the electrodes of a capacitor. Charging the capacitor by a D. C. voltage, the variations in capacity caused by the sound impinging on the thin diaphragm are transformed into voltage variations. One necessary condition is that the charging time constant of the circuit is large enough to keep the capacitor charge constant. To increase the relative variation in capacity, and by this the sensitivity, the stray capacity of the condenser microphone and amplifier input must be as small as possible.

1. Microphone Construction

The microphone cartridge used in this study is a Bruel and Kjaer type 4134, 1/2 inch in diameter. Its performance meets the requirements in the American Standard Z 24.8-1949 for a laboratory standard pressure microphone type L. A sectional view of the mechanical construction of the microphone cartridge is shown in Figure 4.
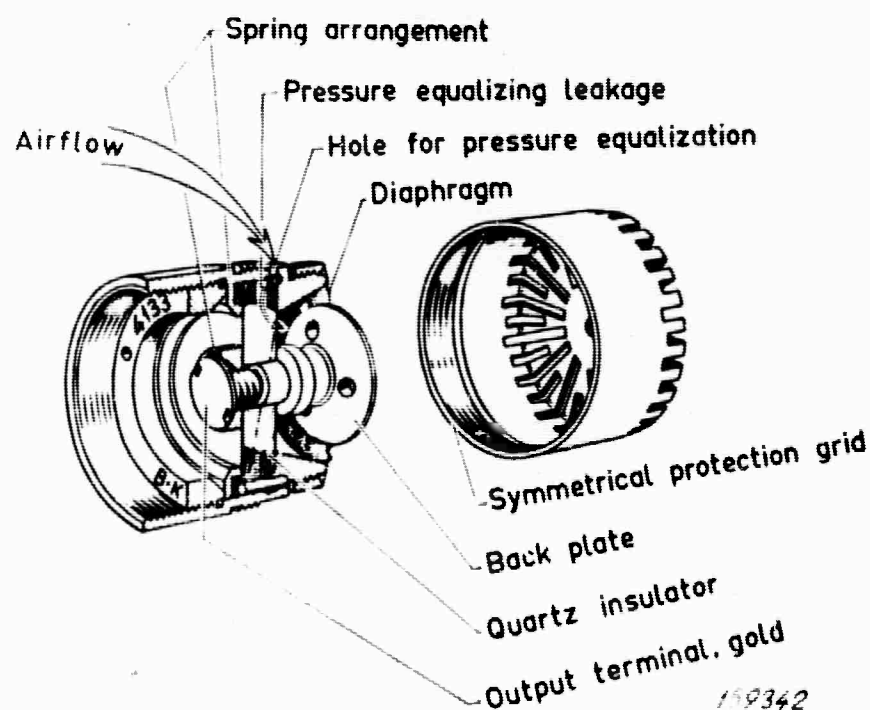

FIGURE 4. SECTIONAL VIEW OF MICROPHONE CARTRIDGE

The cartridge consists of a microphone housing which carries the different parts, such as microphone diaphragm, back plate, insulator, etc. The housing, the diaphragm and back plate are made of nickel and high nickel alloys; secondary parts are nickel-plated brass; the insulator is quartz treated with silicone to increase moisture resistivity; the contact surface of the output terminal is made of gold. In this study the microphone is used without the protection grid.

As seen in Figure 4, the back plate is fixed on the quartz insulator between a collar and a spring-loaded nut. This arrangement ensures a constant distance from the front side of the back plate and the front side of the insulator for constant temperature. The thermal expansion of this distance is approximately $20.10^{-6} \times 13.9\text{-}10^{-6}$ m. per °C for a constant diaphragm tension.

2. Microphone Acoustical Properties

a. Sensitivity

The sensitivity of the microphone measured at the output of the associated cathode follower is within the limits 0.7-1.4 mv/μbar. The calibration chart is shown in Figure 5. Figure 6 indicates a typical sensitivity versus temperature curve.

The ambient pressure, as well as the temperature, will affect the sensitivity of the microphone, which is a major problem area of this study. A pressure equalization on both sides of the diaphragm should take place to avoid erroneous measurements. Equalization is established through a capillary tube which connects the cavity behind the diaphragm with the open air. This connection is not direct and acts as a dirt trap. Displaced from this entry, another tube connects the spacing with the open air at
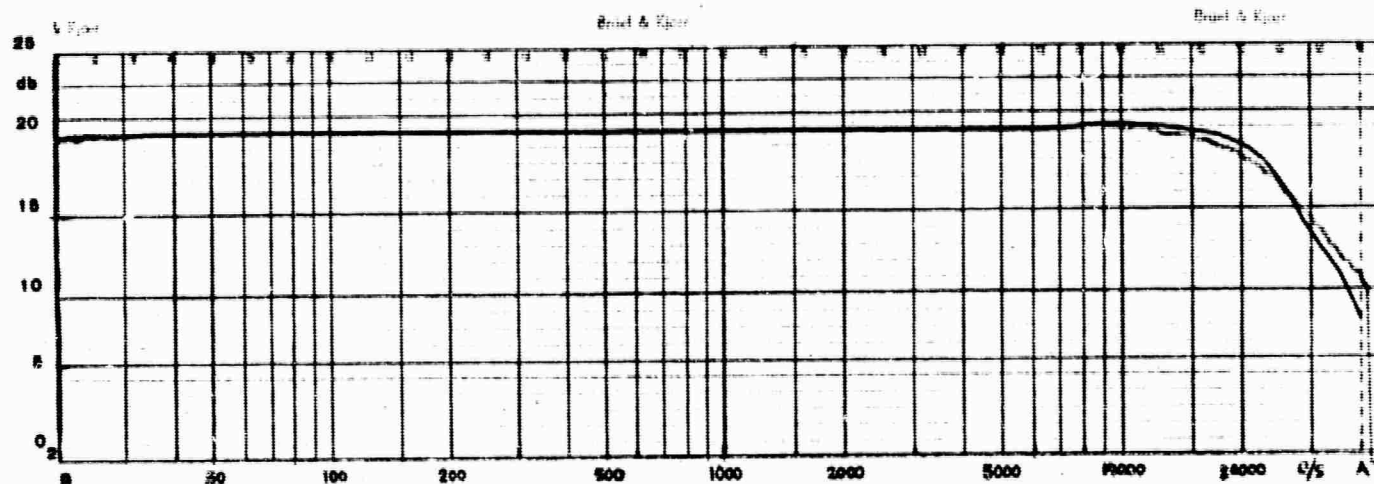
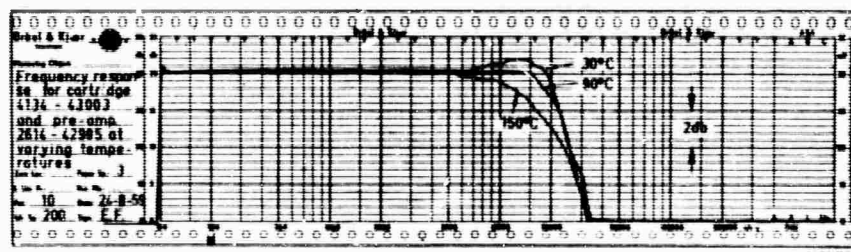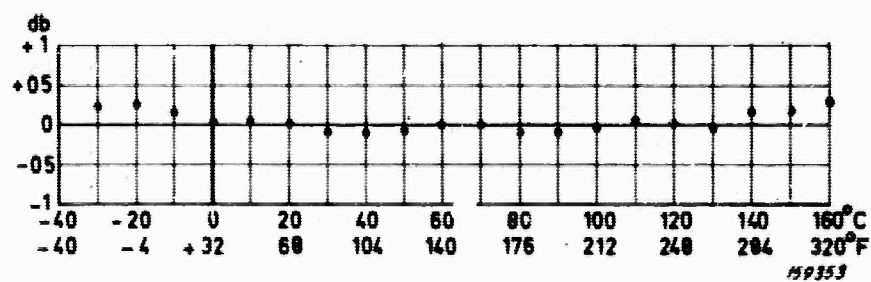FIGURE 5.   MICROPHONE CALIBRATION CHART

FIGURE 6.   MICROPHONE SENSITIVITY TEMPERATURE DEPENDENCE

a point between the diaphragm suspension ring and the housing. This equalization system also keeps the cartridge free from condensed moisture. The steel springs used for clamping the back plate will allow a contact pressure of more than 2.2 lbs.

The pressure equalization is very important under conditions where rapid variations in the ambient static pressure occur. To determine the maximum permissible rate of change in ambient pressure, when the maximum permitted change in microphone sensitivity is given, it is necessary to calculate the air flow through the equalization arrangement. One approach is to consider the electrical analogue of the pressure equalization and to determine the flow resistance of the equalization arrangement, as shown in Figure 7.
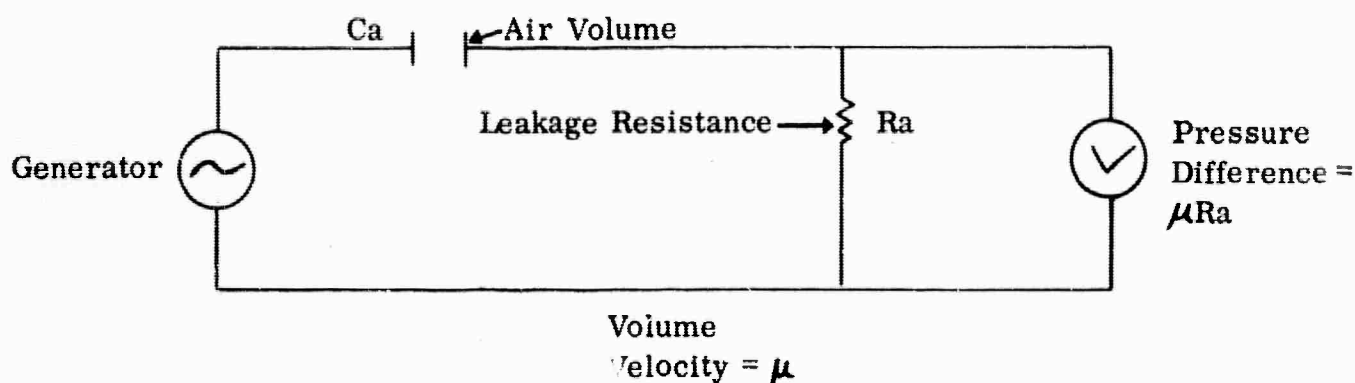

FIGURE 7. EQUIVALENT CIRCUIT OF THE PRESSURE EQUALIZATION

At low frequencies, the internal volume of the cartridge can be considered equivalent to an acoustic capacitor, Ca, and the flow resistance of the pressure equalization arrangement as an acoustic resistor, Ra. The generator represents the sound pressure on the microphone diaphragm. The pressure difference between the outside and inside of the microphone is represented by the voltage drop, Va, across the resistor, Ra.

At higher frequencies, the impedance of the capacitor is negligible compared with Ra, and the pressure difference will be equal to the sound pressure on the diaphragm:

$$Ra = \frac{1}{2\pi f_\mu Ca} = \frac{\rho C^2}{2\pi f \mu V} \text{ in Rayl}$$

where: $C_a = \frac{V}{\rho C^2}$

$f\mu$ = lower limiting frequency (normally 1.0 c/s)

ρ = density of air = 0.0012 g/m^3

C = velocity of sound = 3.44 x 10^4 cm/sec

V = inside volume of cartridge = 0.14 cm^3

The volume velocity, μ , of the air flow through the equalization arrangement is μ = P/Ra where p is the pressure difference across the equalization leak.

The pressure, p, will cause a change of P percent in the microphone sensitivity; this can be calculated when the microphone sensitivity, S, for a certain polarization voltage E_0 is known. A microphone with a low sensitivity will permit a faster change in static pressure than one with a high sensitivity for the same polarization voltage and low frequency cut-off. The microphone sensitivity will vary approximately

1 percent for 9-percent variations in ambient pressure. For greater changes in ambient pressure, the frequency response of the microphone will change, especially toward the higher frequencies. The ambient pressure may change approximately 10 percent per second with less than 1 db change in sensitivity. The pressure equalizing system has a time constant of approximately 0.16 second and permits the equalization of the air pressure on both sides of the diaphragm of the microphone.

b. Frequency Response

The microphone used in this stuoy is designed for measurements with random incidence or those under pressure conditions and has a linear random and pressure characteristic from 20 c/s to 20,000 c/s. Figure 8 shows the frequency characteristics of our microphone under pressure conditions and with sound waves impinging at random angles of incidence to the diaphragm.
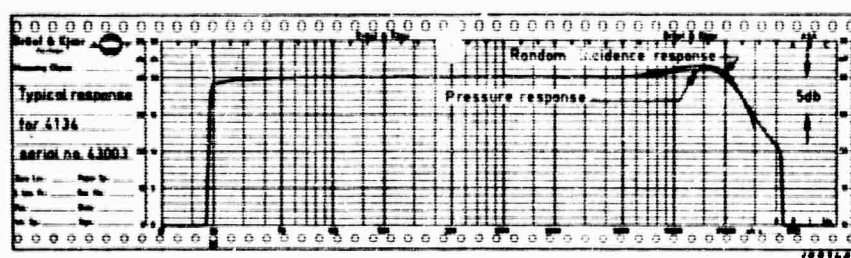

FIGURE 8. FREQUENCY CHARACTERISTICS UNDER PRESSURE
CONDITIONS AND RANDOM ANGLES OF INCIDENCE

3. Microphone Probe

The performance of the probe depends upon the length and width of the tube. The acoustical impedance of the microphone and the volume between the microphone diaphragm and the end of the tube which terminates this volume are also important factors. To obtain the best possible frequency characteristics, a short, wide tube should be used. The tube diameter is very small compared with the wave length, but the tube length will be the same as, or several times larger than, the wave length for a portion of the frequency range under study.

The response for the "probe microphone" is determined by the attenuation of the tube which is given by:

$$\beta = \frac{K\sqrt{\omega}\, 1}{d}$$

where: K = a constant*

ω = angular velocity of pressure variation

1 = tube length

d = tube diameter

The ratio between the characteristic impedance of the tube and the impedance of the acoustical capacitor terminating the microphone end of the probe will change with frequency and will cause a change in response. An equivalent electrical diagram for the probe microphone arrangement is shown in Figure 9. Variation in frequency response can be expected for different tube dimensions. Linear response for low source impedance, low transmission loss, and high impedance of the load can be achieved for

---

* Beranek, L. L, "Acoustical Measurements," J. Wiley and Sons (1959), p. 188.
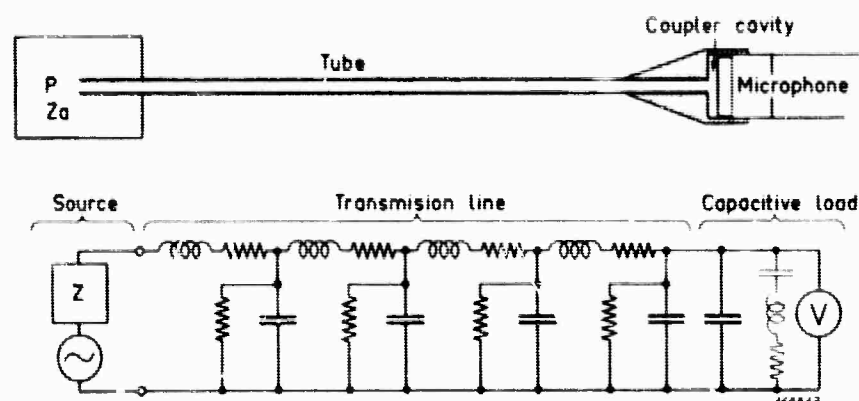
FIGURE 9. EQUIVALENT ELECTRICAL DIAGRAM FOR PROBE MICROPHONE

very short and wide tubes at low frequencies. The drop in sensitivity at higher frequencies becomes greater as longer and narrower tubes are used. For very short and wide tubes and larger coupler cavities, a resonance caused by the mass reactance of the tube in connection with the coupler cavity can act as a Helmholz resonator.

In a probe tube with a sufficiently large bore, as will be used in this study (inside diameter 4 mm), resonance will appear when a 1/4 wave length of the sound wave is equal to the length of the tube for 3/4, 5/4, and 7/4 wave length. This condition is caused by mismatching among the input impedance, the impedance of the tube, and the tube termination. A smoother response will be achieved by adding a damping material to the ends of the tube.

The construction of the probe is shown in Figure 10. The probe tube, made of stainless steel, is pressed into the conical adapter, allowing the microphone to screw into the probe assembly. With the lower edge of the adapter touching the microphone collar, the distance from the diaphragm to the end of the probe tube is approximately 0.2 mm.
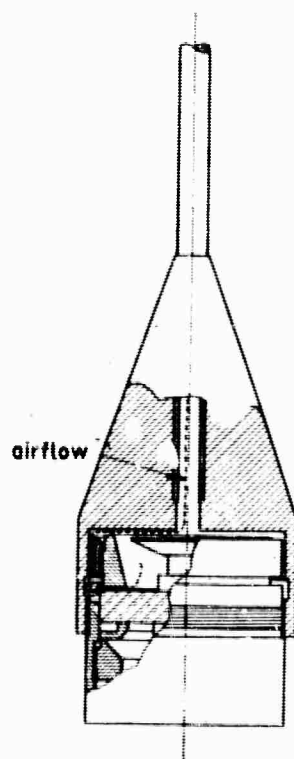
FIGURE 10.   PROBE TUBE MOUNTED ON MICROPHONE
UTILIZING THE PRESSURE EQUALIZATION SYSTEM

Care must be taken so that the probe is more sensitive to sound pressure at the tube input than it is to sound transmission through the side walls due to nonrigidity of the tube or leaks in the adapting piece to the microphone. For shorter tube lengths, this source of interference will be less.

As the active test will be performed behind a barricade, an extension cable will be required from the microphone-cathode follower to the analyzer. The capacity of the extension cable will cause the cathode follower to be loaded, lowering the high frequency cut-off point. However, for the length of cable to be used (approximately 20 feet) and the frequency range that will be covered in this work, this effect will be considerably less than 1 percent distortion at 146 db re. 0.0002 μ bar.

D. Linearity and Instrumentation Tests

Throughout the system it is imperative that the action of each component be linear. Thus, when a sine wave is applied at the driver, it should be radiated (excluding any distortion due to the medium) as a sine wave at the pickup. In this respect it is important to know whether the deformation and general behavior of the diaphragm and its associated components are linear under the action of vibrational forces at a given pressure differential.

The graph of input versus output at any particular frequency should be a straight line. If it deviates from straight-line performance with an increase in input, nonlinear action is present. This is not an infallible test unless the wave form is always sinusoidal. In another test, the input and output wave forms are magnified and applied respectively to two pairs of control plates of a cathode ray oscillograph. In the absence of distortion, the figure is either a straight line or an ellipse.

Initially it appeared that linearity could be established by relating the input voltage of the drive to the output voltage of the microphone. By varying the voltage across the driver, the figure on the scope was observed. It was thought that linearity would be established if the X and Y intercept varied in amplitude with the variation of the voltage across the driver. However, the energy dissipated by the driver diaphragm may not be proportional to the voltage across the driver; therefore, the relationship between the energy input and the energy dissipated must be determined before linearity can be established by this method.

Data were collected on the response of the driver, response of the microphone with probe, linearity of system, and the coupling between the driver and microphone. These tests were performed inside a closed laboratory hood that differed markedly from a satisfactory acoustical environment which would approach free-field plane wave conditions. Although these measurements were not performed in an anechoic chamber, the data did convey usable information, resulting in the following conclusions:

1) The acoustic impedance of the input tube is large.

2) The volume current can be considered constant for a change in termination.

3) The coupling effect between the microphone and driver is negligible.

4) The acoustic impedance of an acoustical material can be determined with the present instrumentation.

It should be noted that the method based on Mawardi's technique is relative, and results of the active test will be interpreted relative to the results of a passive test. The acceptability of the modified apparatus will be established through the medium of the passive test.

An experiment was performed to determine the maximum pressure differential that the driver diaphragm could tolerate. The tone generated by the driver changed at approximately 3 psi and failed at 7 psi. This pressure maximum depends on the frequency.

The response of the microphone was checked as a pressure differential was varied. The output wave form was a pure sine up to a ΔP of 3 psi; at a ΔP of 3.5 psi the wave form was not pure. At a ΔP of 4 psi the output was a straight line, indicating complete failure; the front and rear plates were in contact.

It is interesting to note that investigators at AeroChem Research Laboratories experienced a large attenuation of the sound which was transmitted to the microphone through the exhaust gases of the burning propellant disk (reference 10). As they point out, the average length of travel of sound through the exhaust gases should be kept to a minimum.

A photograph of the pressure system leads with an external view of the large outer pressurized test chamber that has been assembled for the active tests is shown in Figure 11. All materials to be used in pressurization tests and experiments to determine the acceptability of the apparatus have been received.

E. Propellant Selection

Formulation and theoretical performance calculations for the propellant selected for initial testing of the active chamber are presented in Table II. This propellant consists of a polyurethane binder with ammonium perchlorate. Aluminum has been removed from the formulation so that a fairly clean exhaust gas without solid particles could be obtained.

The nominal properties for this formulation are:

Modulus of elasticity	$\sim$ 600 psi
Maximum stress	$\sim$ 100 lb/in^2
Strain at maximum stress	$\sim$ 0.35 in/in
Burning rate	$\sim$ 0.3 in/sec at 1,000 psia

Using this propellant, a total burning time of less than two seconds is anticipated for the 1/2-inch thick by 2-inch diameter test specimen.
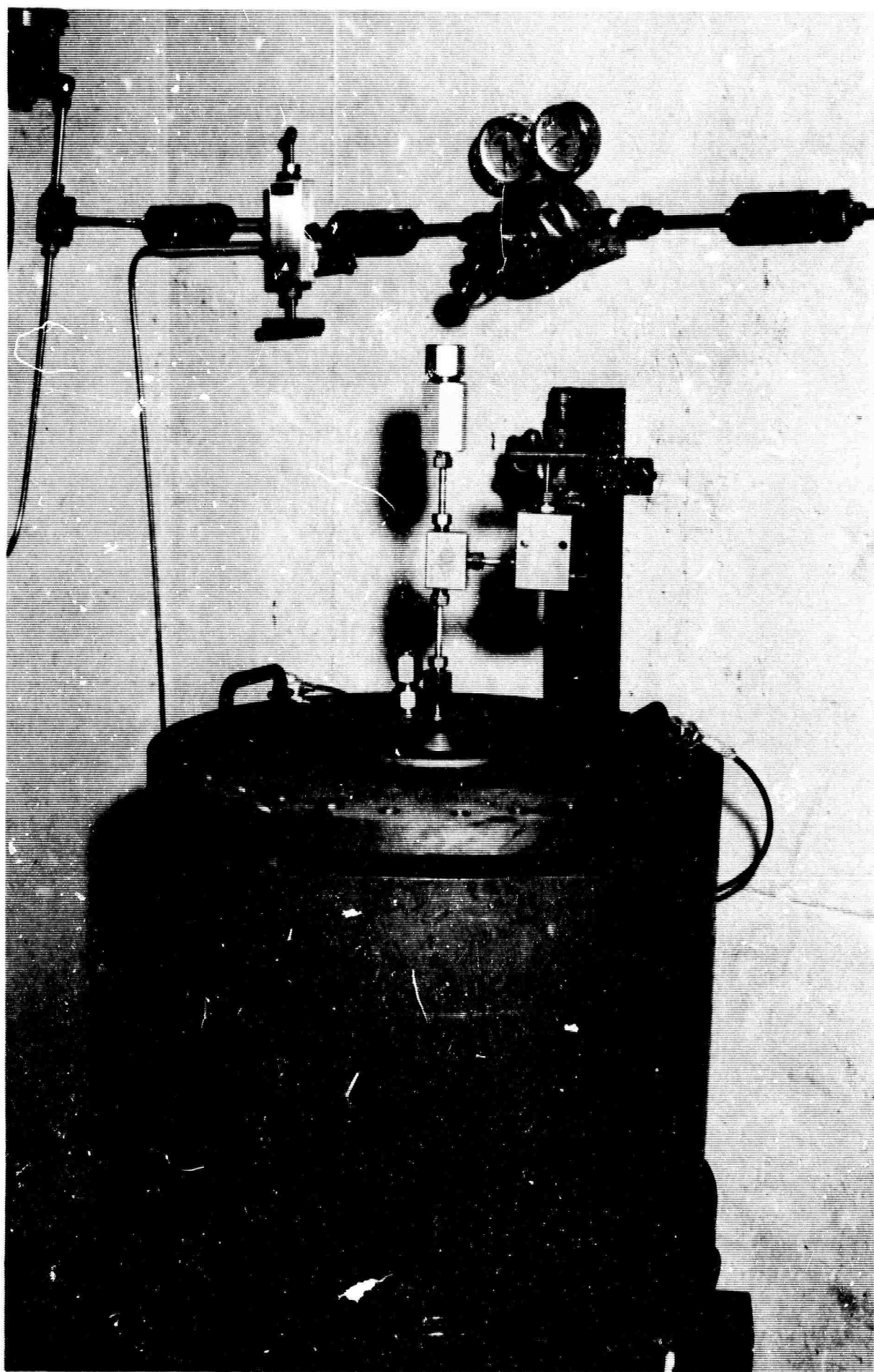
362003   FIGURE 11.   PRESSURIZED TEST CHAMBER

TABLE II

THEORETICAL PERFORMANCE CALCULATIONS

Composition	Percent	ΔH_f (Kcal/mole)	ρ, gm/cc
Z L-320	10	-57.92	1.032
Castor Oil	8	-62.57	0.955
NH_4ClO_4	82	-70.73	1.95

Propellant density (gm/cc), 1.66; Initial temperature, °K, 298.16.

	Chamber	Exhaust
Pressure, atm	68.046	1.00
I_{sp}, sec	--	237.8
γ	1.204	1.239
T, °K	2,679.0	1,224.0
M, grams/mole	24.13	24.20
Cp, cal/gm-°K	0.514	0.426

Mole Percentage of Gaseous Products

	Chamber	Exhaust		Chamber	Exhaust
C	--	--	Graphite	--	--
O	--	--	H	0.215	--
CH	--	--	CO_2	8.585	14.518
H_2O	36.144	30.517	Cl_2	--	--
N_2	8.673	8.705	NH	--	--
O_2	--	--	HCN	--	--
Cl	0.214	--	N	--	--
CO	17.862	12.009	CH_4	--	--
ClO	--	--	H_2	11.516	17.362
NH_3	--	--	NO	0.012	--
NCl	16.1620	16.888	OH	0.152	--

III. FUTURE WORK

During the next quarterly period, effort will be devoted to completing the adaptation of the passive test apparatus to use with burning propellant. Scheduled studies will include investigating propellant at various frequencies, studies of the relationship between exhaust port and acoustic loss, and other tests to determine the suitability of the apparatus for measurements of acoustic impedance. After the apparatus has been determined acceptable, the impedance of a burning propellant surface can be measured.

IV. REFERENCES

1. Mawardi, O. K., "Measurement of Acoustic Impedance," J. Ac. Soc. Am., 21, (March 1949), pp. 84-91.

2. Mawardi, O. K., "Measurement of Acoustic Impedance," ONR Tech Memo b, NR-014-903, May 25, 1949.

3. Thiokol Chemical Corporation, Elkton Division, "Experiments for the Measurement of the Acoustic Impedance of Burning Solid Propellant," Quarterly Report No. 1, E149-61, May 15 - Aug. 15, 1961; October 5, 1961.

4. Beranek, L. L., Jr., Ac. Soc. Am. 12 (July 1940), pp. 14-23.

5. Beranek, L. L., "Acoustic Measurements, " John Wiley and Sons (1959), p. 869.

6. Tukasik, S. J. and Nolle, A. W., "Handbook of Acoustic Noise Control," Vol. I, Supplement 1, WADC Tech. Report 52-204, April 1955.

7. McClure, F. T., Hart, R. W., and Bird, J. F., "Solid Propellant Rocket Motors as Acoustic Oscillators" in Progress in Astronautics and Rocketry, Vol I, Academic Press (1960), pp. 295-358.

8. McClure, F. T., Hart, R. W., and Bird, J. F., "Acoustic Resonance in Solid Propellant Rockets," J. Appl. Phys. 31 (1960), pp. 884-896.

9. Hart, R. W. and McClure, F. T., "Combustion Instability: Acoustic Interaction with a Burning Surface," J. Chem. Phys. 30 (1959), pp. 1501-1514.

10. AeroChem Research Laboratories, Inc., TN-38, " Acoustic Wave Burning Zone Interaction in Solid Propellant," Quarterly Progress Report No. 1, December 1961.

APPENDIX

SUPPLEMENTARY BIBLIOGRAPHY

APPENDIX - SUPPLEMENTARY BIBLIOGRAPHY

The review of open literature, as well as classified publications, for references allied

to this study has been continued. Additional references which were not included in the

bibliography presented in Quarterly Report No. 2 are summarized.

References from the open literature are listed by senior author, while references from

other sources are listed by institutional affiliation.

1. AeroChem Research Laboratories, Inc., "Acoustic Wave Burning Zone Interaction in Solid Propellants," Quarterly Progress Report No. 1, May 1, 1961 - September 30, 1961 (U).

   The experimental method consists of coupling a disk of solid propellant acoustically with a sound generator. Propellant is burned in an anechoic chamber.

2. AeroChem Research Laboratories, Inc., "Acoustic Wave Burning Zone Interaction in Solid Propellants," Quarterly Progress Report No. 2, October 1, 1961 - December 31, 1961; January 1962, TN-40, Contract Nonr 3477 (00), ARPA-23-61 (U).

   Interaction of transmitted sound waves with the flame zones for two composite solid propellants is reported. Interpretation and discussion of results and experimental scatter are noted.

3. Aeronutronic, "Study of Resonance Behavior in Solid Propellants," H. Shanfield, et al, Contract NOrd 17945, Task 2, Quarterly Report No. 15, Publication No. C-1423, October 20, 1961 (C).

   The natural pulsation characteristics of an unaluminized double-base propellant and an aluminized composite propellant were measured directly from the pulsations in thrust produced during steady combustion. Over a range of pressures, results appear to confirm previously drawn conclusions inferred from infrared and visible radiation measurements.

4. Aeronutronic, "Study of Resonance Behavior in Solid Propellants," H. Shanfield, et al., Contract NOrd 17945, Task 2, Quarterly Report No. 16, Publication No. C-1536, January 20, 1962 (C).

Results are discussed of various experimental observations or the "inherent" combustion oscillations of burning solid propellants - characterized by low-frequency pulsations (40-150 cps). One hypothesis proposed is that burning rate can be associated with the emitted infrared radiation under oscillatory conditions. Based on similar response, amplitude-to-pressure data indicate that aluminized propellant is less prone to combustion instability than unaluminized propellant.

5. Applied Physics Lab., Johns Hopkins University, "An Erosion Mechanism for Non-linear Instability in the Axial Modes of Solid Propellant Rocket Motors," F. T. McClure, J. F. Bird, and R. W. Hart, October 1961, Report TG-335-9, NOrd 7386 (U).

The authors investigate the nonlinearity arising from acoustic erosivity. This non-linearity is of first order in the acoustic amplitude, and can be significant even when higher order effects are negligible. A sample calculation of the stability in axial modes is presented. An example illustrates that a motor stable at low acoustic amplitudes can be unstable at moderate amplitudes due to the nonlinearity of erosion.

6. Denison, M. R. and Baum, E., "A Simplified Model of Unstable Burning in Solid Propellants," ARS Journal, Volume 31, No. 8, August 1961. pp. 1112-1122 (U).

An analysis of the surface temperature (hence, mass flux) response of a solid propellant to a disturbance in gas pressure has been developed. Time lags in the gas phase are neglected while transient heat conduction in the solid is considered. Results are obtained by perturbing the conservation equation in both the gas phase and the solid phase. Stability conditions are obtained in terms of a few dimensionless parameters which depend upon the steady state conditions.

7. Hercules Powder Co., Allegany Ballistics Lab., "Combustion Instability," Research Progress Report, Code 2-61-52, May 16, 1961, T. A. Angelus (U).

8. Hercules Powder Co., "Combustion Instability," V. R. Alford, Research Progress Report, Code 2-61-52, April 5, 1961 (U).

9. Hercules Powder Co., "Status of Research and Engineering Projects," ABL/QPR 21, July 1, 1960 (C).

The feasibility of using end-burning motor systems for obtaining information on oscillatory burning in solid propellants is shown. Oscillatory end burners were static fired with an acoustic filter length placed before the nozzle. Heat losses experienced caused a four-second delay in oscillation.

10. Hercules Powder Co., Allegany Ballistics Lab., "Status of Research and Engineering Projects," ABL/QPR-31, Oct. 1, 1961, pp. 77 (C)

   An effort is made to determine the degree of sound propagation through nozzles during unstable burning in a rocket motor.

11. Hercules Powder Co., Allegany Ballistics Lab., "Status of Research and Engineering Projects," ABL/QPR-33, January 1, 1962 (C).

   A program for acoustic admittance experiments with ethyl nitrate is presented. Presently, reasons for inconsistency in data obtained for the liquid system are being investigated.

12. Jet Propulsion Laboratory, "Experimental Studies of Unstable Combustion in Solid Propellant Rocket Motors," E. M. Lanusbaum and F. W. Spaid, Tech. Rep. No. 32-146, August 4, 1961, Contract No. NASw-6 (U).

   Experiments were conducted in which hollow chambers were attached at either the head or nozzle end of the propellant grains. Results indicated neither a frequency-selective nor viscous damping effect but indicated that instability associated with oscillations in the fundamental tangential mode is independent of longitudinal modes. The origin and implications of large torques noted about the motor's longitudinal axis are discussed.

13. Naval Ordnance Test Station, "Measurement Problems in Research on Unstable Combustion of Solid Rocket Propellants," H. B. Mathes, Aug. 1, 1961, NOTS-TP2602 (U).

   Topics included are behavior of several types of high frequency response pressure gauges, difficulties in detecting high frequency pressure oscillations, techniques in recording and storing detected data, and methods used in recovery and analysis of recorded data.

14. New York University, College of Engineering, "High Amplitude Oscillations in Solid Fuel Rocket Motors," M. Richman, Sept. 8, 1961, Nonr 3155 (00) (U).

   Final report on phase 1, a literature and theoretical analysis.

15. Rohm and Haas Co., Redstone Arsenal Research Division, "Oscillatory Burning of Propellants," Quarterly Progress Report on Interior Ballistics, No. p-61-7, Feb. 15-May 15, 1961; Oct. 3, 1961, pp. 1-9 (C).

16. Solovev, V. V., "Vibrational Combustion," Inzh.-Fiz. Zh. 1959, No. 1, 25; Ref. Zh. Mekh. 1959, No. 9, Rev. 9964 (U).

An analysis is made of vibrational combustion in high pressure combustion chambers using pulverized coal and lignite. The frequency of the vibrations was found to be close to the natural frequency of a column of gas in a tube closed at one end. It is concluded that the phenomenon under observation is that of acoustical longitudinal vibration of a column of gas. When there is a favorable phase correlation between the pulsations of heat liberation and of pressure, effected by delaying the firing of the fuel mixture, the vibrational system may be stimulated.

17. Standford Research Institute, "Disturbances at the Surface of Burning Solid Propellants," Tech. Note No. 1, Contract AF 49(638)-565, Project No. 4759, ARPA No. 24-60, Task 2, April 24, 1961, by G. A. Agoston, AFOSR-915 (U).

A study is made of the changes in conditions near the surface of burning liquid nitrate following the impact of a weak plane shock wave (amplitude 0.5 psi) moving in a direction normal to the surface. Preliminary data suggest an influence on flame structure between 109 and 230 $\mathcal{M}$ sec following impact.

18. Thiokol Chemical Corporation, Wasatch Division, "Resonant Burning," Report F61-106, December 18, 1961 (U).

Experiments were conducted on propellant with various percent aluminum additives. Test runs were made in a side-vented end burner equipped with a P_z electric pressure transducer. The effect of an aluminum additive on resonance is shown. Propellants with 0, 0.5, 1, 4, and 8 percent aluminum showed stable, mildly unstable, and, in a few cases, seriously unstable operation at different chamber geometries.

DISTRIBUTION

DISTRIBUTION

Office of Naval Research
Power Branch (Code 426)
Department of the Navy
Washington 25, D. C.
Attn: Dr. Ralph Roberts
(2 copies)

Director, Advanced Research Projects Agency
The Pentagon
Washington 25, D. C.
Attn: Technical Information Officer
(6 copies)

Solid Propellant Information Agency
Applied Physics Laboratory
Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
(3 copies)

Dr. F. T. McClure
Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

Dr. I. Silver
Department of the Navy
Bureau of Naval Weapons (RMMP-11)
Washington 25, D. C.

Special Projects Office
Department of the Navy
Washington 25, D. C.
Attn: LCDR R. L. Mcarthy

Naval Research Laboratory
Washington 25, D. C.
Attn: Dr. M. W. Oleson

Naval Ordnance Test Station
China Lake, California
Attn: Mr. E. W. Price

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. E. Mitchell

National Aeronautics and Space Admin.
1520 H Street
Washington 25, D. C.
Attn: Mr. W. Cohen

Office of Aerospace Research
Department of the Air Force
Washington 25, D. C.
Attn: Mr. J. F. Masi

Ballistic Research Laboratories
Aberdeen Proving Ground
Maryland
Attn: Dr. L. A. Watermeier

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland
Attn: Dr. J. H. Frazer

Allegany Ballistics Laboratory
Hercules Powder Company
Cumberland, Maryland
Attn: Mr. T. A. Angelus

Polytechnic Institute of Brooklyn
333 Jay Street
Brooklyn, New York
Attn: Professor R. D. Agosta

United Technology Corporation
P. O. Box 358
Sunnyvale, California
Attn: Dr. D. Altman

Grand Central Rocket Company
P. O. Box 111
Redlands, California
Attn: Dr. A. T. Camp

Office of Chief of Ordnance
Research and Development
Department of the Army
Washington 25, D. C.
Attn: Mr. J. A. Chalmers

Aerojet-General Corporation
Azusa, California
Attn: Dr. R. L. Lou

Aerojet-General Corporation
Azusa, California
Attn: Mr. R. F. Chaiken

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor S. I. Cheng

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor L. Crocco

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor M. Summerfield

Princeton University
James Forrestal Research Center
Princeton, New Jersey
Attn: Professor J. Fenn

Harvard University
Department of Mechanical Engineering
Cambridge, Massachusetts
Attn: Professor H. W. Emmons

Chesapeake Instrument Company
Shadyside, Maryland
Attn: Mr. J. W. Fitzgerald

Atlantic Research Corporation
Alexandria, Virginia
Attn: Dr. R. Friedman

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena 3, California
Attn: Dr. E. M. Landsbaum

Quantum Dynamics
19458 Ventura Boulevard
Tarzana, California
Attn: Dr. F. F. Liu

California Institute of Technology
Pasadena, California
Attn: Professor F. T. Marble

Cornell Aeronautical Laboratory
Buffalo, New York
Attn: Dr. G. Markstein

Lockheed Aircraft Corporation
Missile Systems Division
Sunnyvale, California
Attn: Dr. W. Nachbar

Stanford Research Institute
Menlo Park, California
Attn: Dr. P. L. Nichols

University of Utah
Salt Lake City, Utah
Attn: Professor N. W. Ryan

Rohm and Haas Company
Redstone Arsenal
Huntsville, Alabama
Attn: Dr. H. M. Shuey

Rocketdyne
6633 Canoga Avenue
Canoga Park, California
Attn: Dr. R. Thompson

Armour Research Foundation
10 West 35th Street
Chicago, Illinois
Attn: Dr. T. P. Torda